INVERSE PROBLEMS IN HYDROLOGIC RADIATIVE TRANSFER

Howard R. Gordon
Department of Physics
University of Miami
Coral Gables, FL 33124

Voice: (305) 284-2323-1, Fax: (305) 284-4222, email: gordon@phyvax.ir.miami.edu
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LONG-TERM GOAL

The long-term scientific goal of my research is to better understand the distribution of phytoplankton in the world's oceans through remote sensing their influence on the optical properties of the water.

SCIENTIFIC OBJECTIVES

Optically, phytoplankton reveal their presence through their influence on the inherent optical properties (IOP's) of the water. The main effect of phytoplankton is to increase the absorption of light by virtue of the strong absorption by their photosynthetic (chlorophyll a) and accessory pigments. A secondary effect is to increase the backscattering coefficient of the medium in a manner that depends on the concentration of pigments. Although techniques for measuring the absorption coefficient directly (e.g., in-situ AC9 measurements or in-vitro filterpad absorption) are becoming accepted by the scientific community, laboratory techniques for measuring backscattering are tedious and subject to error, and in-situ techniques for backscattering are in their infancy. In addition, in most in-situ measurements the volume of medium that is sampled is small and may not be representative of the whole waterbody, even in a homogeneous medium. Thus, in the past, there has been considerable effort devoted toward indirectly inferring these IOP's by virtue of their affect on the apparent optical properties (AOP's), e.g., the diffuse reflectance of the water (the color of the water) or the downwelling irradiance attenuation coefficient. These AOP's are perhaps the most frequently measured quantities in hydrologic optics. Clearly, interpretation of such observations requires a detailed understanding of the influence of phytoplankton on the IOP's, and their link to the AOP's.

The IOP <--> AOP link forms the focus of the present research. In particular, our research is centered on deriving the IOP's from measurements of the AOP's. This is an example of the inverse problem of radiative transfer. It is important in that IOP's

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determined from AOP's are, by definition, sampled at a scale appropriate for radiative transfer. Also, the retrieved IOP's possess the attribute that when combined with the radiative transfer equation, they reproduce the measured AOP's. In the present research, we focus on deriving the vertical profiles of the absorption and backscattering coefficients from measurements of the vertical profiles of downwelling irradiance and either upwelling radiance or upwelling irradiance.

APPROACH

Our approach is to use methods my coworkers and I have developed to retrieve aerosol properties from measurements of the radiance distribution in the atmosphere (Wang and Gordon, 1993; Gordon and Zhang, 1995). Briefly, given the measured AOP's, we use trial IOP's for solving the radiative transfer equation (RTE) to generate trial AOP's, which are then compared to the measurements. Based on the error in the trial AOP's, we vary the trial IOP's in a manner as to produce better agreement between the measurements. This is carried out in an iterative fashion with the RTE solved using the new trial IOP's at each step in the iteration (Gordon and Boynton, 1997). The resulting profiles of the absorption and backscattering coefficients have the attribute that they yield AOP's that agree with the measurements. The results are remarkably insensitive to the scattering phase function assumed for the ocean as long as it is reasonably realistic. Furthermore, Gordon and Boynton (1997) showed that in the homogeneous-ocean case, the inversion procedure could be carried out in the presence of a highly-reflecting sea bottom.

We have solved the RTE the ocean-atmosphere system under a wide range of environmental (ocean and atmosphere) conditions. These solutions provide realistic radiance and irradiance profiles under conditions in which the IOP's *are precisely known*, and have been used to provide “experimental” data to test various inversion algorithms. However, we are now testing the algorithm using experimental data in collaboration with J. Mueller and J.R.V. Zaneveld.

We are also in the process of exploring the influence of variations in the sea-bottom albedo and bi-directional reflectance distribution function (BRDF) on homogeneous-waterbody retrievals.

WORK COMPLETED

We developed an algorithm for retrieving vertical profiles of the absorption and backscattering coefficients for a vertically stratified ocean by measuring the vertical profiles of the AOP's, the downwelling irradiance, and the upwelling radiance or irradiance. The algorithm is an extension of that given by Gordon and Boynton (1997). A study was carried out to understand the sensitivity of the retrieved coefficients to (1) assumptions regarding the scattering phase function of the medium and its vertical variation, (2) noise in the irradiance measurements, (3) errors in the radiance measurements, (4) the magnitude of the vertical variation in IOP's (i.e., the severity of the stratification), and (5) the effects of incident illumination.

We have completed a 3-D backward Monte Carlo code for generating pseudodata for a homogeneous ocean with position dependent optical properties.

RESULTS

We completed an algorithm for inverting downwelling irradiance and either upwelling radiance or upwelling irradiance profiles to retrieve profiles of the absorption and backscattering coefficients. The algorithm includes all significant orders of multiple scattering. It is an extension to a vertically stratified ocean of that given by Gordon and Boynton (1997) for a homogeneous ocean. The main feature of the extension is a method for estimating the backscattering coefficient at each depth (z) from the irradiance reflectance and its derivative at z, based on the work of Gordon and Clark (1980) concerning the behavior of the diffuse reflectance of a vertically stratified medium. An important feature of the algorithm is that it does not require knowledge of the scattering phase function of the medium; however, we have found that the results for the backscattering coefficient are better the closer the phase function assumed in the algorithm is to the true phase function. In contrast, excellent retrievals of the absorption coefficient can be obtained with a very inaccurate phase function. When the spacing between the AOP data samples is sufficiently small that the derivatives of the irradiances can be accurately computed, the simulations suggest that the algorithm is capable determining the vertical structure of a stratified water body, and usually provides the absorption coefficient profile with an error less than about 2% and the backscattering coefficient profile with an error less than about 10%. In general, the error in the retrieved absorption coefficient is approximately equal to the error in determining the downwelling irradiance attenuation coefficient from the downwelling irradiance data. The effect of noise in the data on the retrievals is, for the most part, manifest through its influence on the determination of the downwelling irradiance attenuation coefficient.

IMPACT

Development of a method for inverting irradiance profiles to obtain the IOP's in vertically stratified waters is a significant accomplishment. We believe that the algorithm will be of significant utility for processing existing and future experimental irradiance profile data to estimate the absorption and backscattering coefficients, and their relationship to constituent concentrations, for use in ocean color remote sensing algorithms. Furthermore, the algorithm provides IOP's that are, by definition, sampled at a scale appropriate for radiative transfer, and therefore, will be of significant value for examining questions of closure concerning traditional IOP-instruments that sample at scales of a few cubic centimeters.

TRANSITIONS

We are in the process of preparing a package of homogeneous-ocean software for S. Gallegos (NRL) to use for analysis of irradiance data acquired in the Yellow Sea. As the vertically-stratified algorithm becomes more mature, we envisage making it available to the community in a "user friendly" form.

RELATIONSHIPS

We are working with J. Mueller and J.R.V. Zaneveld to compare our estimates of absorption and backscattering profiles from downwelling irradiance and upwelling radiance with direct measurements using in-situ instrumentation. We expect this work will contribute to AOP-IOP closure. Their work is funded by NASA.

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